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Simple classification of final state interaction effects in $^4He(e,e'p)$ scattering

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A b s t r a c t

The radius of interaction between the struck proton and spectator nucleons is close to the radius of short-distance two-nucleon correlations in nuclear matter, which makes final state interaction (FSI) an important background to production of protons with large missing momentum. We present a simple classification of the dominant FSI effects in $^4He(e,e'p)$ scattering and identify parts of the phase space dominated by FSI. At large missing momentum, final state interaction leads to a striking angular anisotropy of the missing momentum distribution, which has a prominent peak in transverse kinematics and smaller, forward-backward asymmetric, peaks in parallel kinematics.

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Quasielastic $(e, e'p)$ scattering on nuclei at large missing momentum p_m is a relevant tool for investigation of short-distance nucleon-nucleon interaction (initial state two-nucleon correlations (ISC)) in the nuclear medium [1] and constitutes an important part of the CEBAF experimental program [2]. The measured p_m distribution is distorted by final state interaction (FSI) of the struck proton in the target nucleus debris. The point we wish to make in this paper is that, in the CEBAF range of energies, the radius b_o of the FSI is very close to the radius r_c of ISC (see below). This makes FSI an important background in the production of protons with large p_m, which may obscure the relationship between the observed p_m distribution and the ISC. Indeed, a strong effect of FSI in $(e, e'p)$ scattering on C and Pb nuclei was found in [3].

In this note we present simple estimates of the effect of FSI in $^4He(e, e'p)$ scattering. We show how FSI leads to an anisotropic p_m distribution, with the dominance of FSI effects in transverse kinematics and significant FSI corrections to ISC effects in parallel kinematics. This last point can be important for the y-scaling analysis. We find a novel effect of quantum-mechanical interference of ISC and FSI which gives a large correction to the elastic rescattering of the struck proton and which must be included when discussing more sophisticated features of FSI such as color transparency effects [4]. The emphasis of this paper is on the classification of FSI effects and on semi-analytic estimates of the relative magnitude of FSI and ISC effects. We concentrate on the region of 4-momentum transfer squared $Q^2 \gtrsim (1\text{-}2)\text{GeV}^2$, which is relevant to the planned CEBAF experiments [2]. Furthermore, in this range of Q^2, FSI can be described by Glauber's multiple scattering theory [5], which simplifies the evaluation of FSI effects.

The reduced nuclear amplitude for the exclusive process $^4He(e, e'p)A_f$ is given by

$$\mathcal{M}_f = \int d\vec{R}_1 \, d\vec{R}_2 \, d\vec{R}_3 \Psi_f^*(\vec{R}_1, \vec{R}_2) S(\vec{r}_1, ..., \vec{r}_4) \Psi(\vec{R}_1, \vec{R}_2, \vec{R}_3) \exp(i\vec{p}_m \vec{R}_3) \tag{1}$$

where $\Psi(\vec{R}_1, \vec{R}_2, \vec{R}_3)$ and $\Psi_f(\vec{R}_1, \vec{R}_2)$ are wave functions of the target ^4He nucleus and of the specific 3-body final state A_f, which are conveniently described in terms of the Jacobi coordinates $\vec{R}_1 = \vec{r}_2 - \vec{r}_1$, $\vec{R}_2 = \frac{2}{3}\vec{r}_3 - \frac{1}{3}(\vec{r}_1 + \vec{r}_2)$, $\vec{R}_3 = \vec{r}_4 - \frac{1}{3}(\vec{r}_1 + \vec{r}_2 + \vec{r}_3)$ (plus $\vec{R}_{cm} = \frac{1}{4}\sum_i \vec{r}_i \equiv 0$). Lab coordinates $\{\vec{r}_i(\vec{R}_j, \vec{R}_{cm})\}$ are also used in the text for

sake of intuition. The nucleon "4" of ^4He is chosen for the detected struck proton with momentum $\vec{p}$, $\vec{p}_m \equiv \vec{q} - \vec{p}$ is the missing momentum, $\vec{q}$ is the (e, e') momentum transfer and $S(\vec{r}_1, ..., \vec{r}_4)$ is the S-matrix of the FSI of the struck proton with three spectator nucleons. In this paper we discuss the quantity $\sum_f |M_f|^2$, which gives the inclusive spectrum of protons in $^4He(e', e)$ scattering in quasielastic kinematics. Summing over all the allowed final states A_f for the three undetected nucleons, the closure relation

$$\sum_f \Psi_f(\vec{R}_1{}', \vec{R}_2{}')\Psi_f^*(\vec{R}_1, \vec{R}_2) = \delta(\vec{R}_1 - \vec{R}_1{}')\delta(\vec{R}_2 - \vec{R}_2{}') \tag{2}$$

leads to [1]

$$w(\vec{p}_m) = \sum_f |\mathcal{M}_f|^2 = \int d\vec{R}_1 \, d\vec{R}_2 d\vec{R}_3{}' d\vec{R}_3 \exp\left[i\vec{p}_m(\vec{R}_3 - \vec{R}_3{}')\right]$$
$$\times \Psi^*(\vec{R}_1, \vec{R}_2, \vec{R}_3{}')S^\dagger(\vec{r}_1{}'.., \vec{r}_4{}')S(\vec{r}_1, ..., \vec{r}_4)\Psi(\vec{R}_1, \vec{R}_2, \vec{R}_3). \tag{3}$$

In the absence of FSI, $w(\vec{p}_m)$ coincides with the familiar single-particle momentum distribution $n_F(p_m)$, extensive studies of which are available in the literature [7]. High-$\vec{p}_m$ Fourier components in Eq. (3) come from the rapid variation of the integrand with $|\vec{R}_3 - \vec{R}_3'|$, which originates from either ISC or FSI. In the following, "long ranged" will indicate all the functions which change on the scale of the ^4He radius $R_o \approx 1.4 fm$ ([8,9], for more accurate definition see below), while "short ranged" refers to changes on the scale of the correlation radius $r_c \sim 0.5 fm$ [10] and/or the FSI radius b_0. A simple way of modeling the ISC effect is

$$\Psi(\vec{R}_1, \vec{R}_2, \vec{R}_3) \equiv \Psi_o(\vec{R}_1, \vec{R}_2, \vec{R}_3)F, \quad \text{where} \quad F \equiv \prod_{i<j}^4 \left[1 - C(\vec{r}_i - \vec{r}_j)\right]. \tag{4}$$

Here Ψ_o is a (long range) mean field wavefunction, and $C(\vec{r})$ is a short range correlation function. For a hard core repulsion $C_o = C(0) = 1$, for a soft core $C_o < 1$. At the large Q^2 of interest in the CEBAF experiments, FSI can be described by Glauber theory. Defining transverse and longitudinal components $\vec{r}_i \equiv (\vec{b}_i + z_i\hat{q})$ and $\vec{R}_i \equiv (\vec{B}_i + Z_i\hat{q})$ we can write

$$S(\vec{r}_1, ..., \vec{r}_4) = \prod_{i=1}^3 \left[1 - \theta(z_i - z_4)\Gamma(\vec{b}_4 - \vec{b}_i)\right], \tag{5}$$

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[1] The related formula of Ref.[6] introduces an extraneous factor $\frac{3}{4}$ in the exponent of the Fourier transform. A consistent treatment of the center of mass motion of the 3-body final state leads to our Eq. (3).

where $\Gamma(\vec{b})$ is the profile function of the nucleon-nucleon scattering

$$\Gamma(\vec{b}) \equiv \frac{\sigma_{tot}(1 - i\rho)}{4\pi b_o^2} \exp\left[-\frac{\vec{b}^2}{2b_o^2}\right] \tag{6}$$

(ρ is the ratio of the real to imaginary part of the forward elastic scattering amplitude). The Glauber formalism describes quite well nucleon-nucleus scattering at energies from 500 MeV to many GeV, even at angles as large as 30° at 500 MeV (for a review see [11]). At $T_{kin} \sim 1\text{GeV}$ $b_o \approx 0.5 fm$ and $\sigma_{tot} \approx 40\text{mb}$ [11,12,13].

Because of $r_c^2, b_o^2 \ll R_o^2$, the rapid variation of the integrand of $w(\vec{p}_m)$ comes from

$$FF^+ SS^+ = \prod_{i<j}^{4}\left[1 - C(\vec{r_i}' - \vec{r_j}')\right]\left[1 - C(\vec{r_i} - \vec{r_j})\right]$$
$$\times \prod_{i\neq 4}\left[1 - \theta(z_i' - z_4')\Gamma^*(\vec{b_4}' - \vec{b_i}')\right]\left[1 - \theta(z_i - z_4)\Gamma(\vec{b_4} - \vec{b_i})\right] =$$
$$1 - \sum_{i<j}[C' + C] - \sum_{i\neq 4}[\Gamma' + \Gamma] + \sum[C'\Gamma + C\Gamma'] + \sum C'C + \sum \Gamma'\Gamma + ... \tag{7}$$

The inequalities $r_c^2, b_o^2 \ll R_o^2$ allow to develop a simple classification of ISC and FSI effects, which have different $\vec{p}_m$ dependence and absolute normalization. It is convenient to demonstrate these properties upon the "exactly soluble" model with the harmonic oscillator (HO) mean field wave function

$$\Psi_o \propto \exp\left[-\frac{1}{2R_o^2}\sum_i^4 \vec{r_i}^2\right] = \exp\left[-\frac{1}{4R_o^2}\left(\vec{R_1}^2 + 3\vec{R_2}^2 + \frac{3}{2}\vec{R_3}^2\right)\right] \tag{8}$$

and the simple parameterization for the correlation function $C(r) = C_o \exp\left(-r^2/2r_c^2\right)$.

First, let us comment briefly on ISC effects neglecting FSI. To the zeroth order in $C(\vec{r_i} - \vec{r_j})$, the correlations are not present at all. The resulting p_m distribution vanishes rapidly at $p_m \gtrsim k_F \sim 1/R_o$. In the HO model (8) one finds

$$w(1; \vec{p}_m) = w_1 \exp\left(-\frac{4}{3}R_o^2 p_m^2\right). \tag{9}$$

($w(1; \vec{p}_m)$, $w(C; \vec{p}_m)$,... indicate the contributions to $w(\vec{p}_m)$ coming from the "1","C",... terms in eq.(7)).

Analogous contributions (but smaller in magnitude by the factor $\propto (r_c/R_0)^3$) come from the terms which are linear in $C(\vec{r_i} - \vec{r_j})$: their short range behaviour is averaged

away by the integrations in $dR_1 dR_2$. With the choice (8) one finds

$$w(C; \vec{p}_m) \approx -w_1 C_o 4 \sqrt{\frac{243}{125}} \left(\frac{r_c}{R_o}\right)^3 exp\left[-\frac{4}{5} R_o^2 p_m^2\right]. \tag{10}$$

For the sake of brevity, we don't show here correction factors $[1 + \mathcal{O}(r_c^2/R_o^2)]$ to slopes and normalization factors in eq. (10),(11),(13)-(20). They will be presented elsewhere [14]. They are anyway included in exact form in all the numerical results to be presented below.

The large-p_m component of the momentum distribution comes from the three identical terms of the form $C(\vec{r}_4 - \vec{r}_i)C(\vec{r}_4{}' - \vec{r}_i{}')$. The corresponding contribution $w(C'C; \vec{p}_m)$ to $w(\vec{p}_m)$ directly probes $C(\vec{r})$:

$$w(C'C; \vec{p}_m) \approx w_1 \sqrt{\frac{243}{512}} \frac{1}{R_0^6} \frac{1}{(2\pi)^3} \left| \int d^3\vec{R}_3 C(\vec{R}_3) \exp(i\vec{p}_m \vec{R}_3) \right|^2$$

$$\approx w_1 C_o^2 \sqrt{\frac{243}{512}} \left(\frac{r_c}{R_o}\right)^6 \exp\left(-r_c^2 p_m^2\right) \tag{11}$$

Notice the small normalization factor $\propto (r_c/R_o)^6$. With $r_c = 0.5$fm, $C_o = 1$ and $R_o = 1.4 fm$, the above estimated $w(C'C; \vec{p}_m)$ is in good agreement with the tail of $n_F(p_m)$ as given by Ciofi degli Atti et al [7]. All the above discussed terms give an isotropic $\vec{p}_m$ distribution.

The classification of FSI effects is very similar to the above with one important difference: $C(\vec{r}_4 - \vec{r}_i)$ is a short-ranged isotropic function of $|\vec{r}_4 - \vec{r}_i|$, whereas $\Gamma(\vec{b}_4 - \vec{b}_i)\theta(z_i - z_4)$ is a short-ranged function of the transverse separation $|\vec{b}_4 - \vec{b}_i|$ only. In the longitudinal direction the FSI operator behaves as a long-ranged one, which leads to the angular anisotropy of FSI effects. We decompose $\vec{p}_m \equiv (\vec{p}_\perp + p_{m,z}\hat{q})$. Evidently, the $p_\perp$ dependence of terms linear in $\Gamma(\vec{b}_4 - \vec{b}_i)$ is the same as in Eq.(10) with r_c substituted for b_0. The dependence on $p_{m,z}$ will be more similar to that in Eq.(9), apart from distortions at large $p_{m,z}$ coming from the high frequency Fourier components of $\theta(z_i - z_4)$. Furthermore, the finite real part of the forward pN scattering amplitude leads to a forward-backward asymmetry of the $p_{m,z}$ distribution [15]. The distortion and asymmetry effects (which can be clearly seen in the figures 1 and 2) will be discussed in more detail elsewhere [14]. For

each Γ we have the normalization

$$Y = \frac{b_o^2}{R_o^2} \cdot \frac{\sigma_{tot}}{4\pi b_o^2} = \frac{\sigma_{tot}}{4\pi R_o^2} \approx 0.17 \tag{12}$$

(see eq.(6); b_o^2/R_o^2 comes from the integration) which is larger than the normalization in (10) by a factor $\sim (R_o/r_c)$. The linear FSI terms give negative-valued contributions to $w(\vec{p}_m)$, expressing the direct reduction of the proton flux by FSI. At large $p_\perp$, the leading FSI component of $w(\vec{p}_m)$ comes from the terms $\propto \Gamma(\vec{b}_4 - \vec{b}_i)\Gamma^*(\vec{b}_4' - \vec{b}_i')$, which describe the elastic rescattering of the struck proton on the spectator nucleon "i":

$$w(\Gamma'\Gamma; \vec{p}_m) \propto \left| \int d^2\vec{B}_3 \Gamma(\vec{B}_3) \exp(i\vec{p}_\perp \vec{B}_3) \right|^2 = 4\pi \frac{d\sigma_{el}}{dp_\perp^2} = \frac{1}{4}\sigma_{tot}^2(1 + \rho^2) \exp(-b_o^2 p_\perp^2) \tag{13}$$

Because of $b_o \approx r_c$ in the CEBAF range of Q^2, the $w(C'C; \vec{p}_m)$ and $w(\Gamma'\Gamma; \vec{p}_m)$ components have similar $p_\perp$ dependence. However (compare eqs. (10) and (12)) the overall normalization is larger for the FSI term. So at $p_{m,z} = 0$ we find a strong dominance of the FSI rescattering effect over the ISC effect:

$$\frac{\Gamma'\Gamma}{C'C} \approx \frac{1}{C_o^2\sqrt{6}} \cdot \left[\frac{\sigma_{tot}}{4\pi r_c^2} \right] \cdot \left(\frac{R_o}{r_c} \right)^2 \sim 7. \tag{14}$$

Because the FSI are long-ranged in $z_4 - z_i$, $w(\Gamma'\Gamma; \vec{p}_m)$ decreases steeply with $p_{m,z}$ on the scale $\sim k_F$, which leads to an angular anisotropy of the elastic rescattering effect. The effect of quantum-mechanical interference of ISC and FSI comes from the terms $\propto C(\vec{r}_4' - \vec{r}_i')\Gamma(\vec{b}_4 - \vec{b}_i)$ and $\propto C(\vec{r}_4 - \vec{r}_i)\Gamma^*(\vec{b}_4' - \vec{b}_i')$. The corresponding contribution $w(C\Gamma' + C'\Gamma; \vec{p}_m)$ to $w(\vec{p}_m)$ has the $p_\perp$ dependence

$$w(C\Gamma' + C'\Gamma; \vec{p}_m) \propto \exp\left[-\frac{1}{2}(r_c^2 + b_o^2)p_\perp^2 \right], \tag{15}$$

steep $p_{m,z}$ dependence similar to that in Eq.(10), and the large normalization

$$\frac{C\Gamma' + C'\Gamma}{\Gamma'\Gamma} = 4\sqrt{\frac{3}{5}}C_o \left(\frac{4\pi r_c^2}{\sigma_{tot}} \right) \cdot \frac{r_c}{R_o} \sim 1. \tag{16}$$

Notice that any quasiclassical consideration would completely miss this large ISC-FSI interference effect.

The leading ISC correction to the elastic rescattering effect comes from the terms $\propto C(\vec{r}_4 - \vec{r}_i)\Gamma(\vec{b}_4 - \vec{b}_i)\Gamma^*(\vec{b}_4{}' - \vec{b}_i{}')$, which have the $p_\perp$ dependence with the slope

$$\frac{1}{2}\left(b_o^2 + \frac{b_o^2 r_c^2}{b_o^2 + r_c^2}\right) < b_o^2, \tag{17}$$

a steep $p_{m,z}$-dependence (as in Eq.(11)) and the normalization

$$\frac{C\Gamma'\Gamma + C'\Gamma'\Gamma}{\Gamma'\Gamma} = -2C_o\sqrt{\frac{3}{5}} \cdot \frac{r_c^2}{b_o^2 + r_c^2} \cdot \frac{r_c}{R_o} \sim -0.3. \tag{18}$$

These corrections are not small. In a different form, a similar result is contained in Eq. (7) of Ref. [3]. The FSI correction to the ISC effect comes from terms $\propto C(\vec{r}_4{}' - \vec{r}_i{}')C(\vec{r}_4 - \vec{r}_i)\Gamma(\vec{b}_4 - \vec{b}_i)$, which give

$$w(C'C\Gamma + C'C\Gamma'; \vec{p}_m) \propto \exp(-r_c^2 p_{m,z}^2)\exp\left[-\frac{1}{2}\left(\frac{b_o^2 r_c^2}{b_o^2 + r_c^2} + r_c^2\right)p_\perp^2\right], \tag{19}$$

slow decrease with p_z and the relative normalization

$$\frac{C'C\Gamma + C'C\Gamma'}{C'C} \approx -\frac{r_c^2}{r_c^2 + b_o^2} \cdot \frac{\sigma_{tot}}{4\pi r_c^2} \sim -\frac{2}{3}. \tag{20}$$

This is reminiscent of the large probability of double-scattering in a small deuteron-like 2-particle cluster of size $\sim r_c$ [5]. One can evaluate the still higher-order terms $\propto C(\vec{r}_4{}' - \vec{r}_i{}')C(\vec{r}_4 - \vec{r}_i)\Gamma(\vec{b}_4 - \vec{b}_i)\Gamma^*(\vec{b}_4{}' - \vec{b}_i{}')$, which have a broad $(p_\perp, p_{m,z})$-distribution, but small absolute normalization [14].

In Fig. 1 we show the angular dependence of $w(\vec{p}_m)$ and its most important components at large p_m. The large-p_m tail of the undistorted distribution $n_F(p_m)$ is borrowed from ref. [7]. For the elastic rescattering $w(\Gamma'\Gamma; \vec{p}_m)$ and the ISC-FSI interference $w(C\Gamma' + C'\Gamma; \vec{p}_m)$ we take our results (shown in approximated form in eqs. (13),(14) and (17),(18), respectively). We find a prominent signal of the elastic rescattering and ISC-FSI interference in parallel kinematics. Notice a significant forward-backward asymmetry of the ISC-FSI interference component $w(C\Gamma' + C'\Gamma; \vec{p}_m)$, which is generated by the real part of the pN scattering amplitude, and also the unexpectedly large contribution from the elastic rescattering term at $p_\perp = 0$, which comes from the θ-function generated tail of the p_z distributions. To illustrate this general FSI effect, in Fig. 2 we show what happens if one

substitutes $\frac{1}{4}$ for the product of $\theta(z_i - z_4)$ and $\theta(z_i - z_4')$. The distortion effect becomes stronger at larger p_m, leading to the forward and backward peaks alongside the FSI peak in the transverse kinematics. This could influence the y-scaling analysis (see also [19]).

Summarizing the main results, we have presented a simple classification of FSI effects compared to the ISC effects. The anisotropic angular dependence of the elastic rescattering and ISC-FSI interference effects compared to the isotropic momentum distribution in the PWIA is a striking signature of FSI effects. An important finding is that apart from the peak at 90°, distortions by FSI lead also to forward and backward peaks, which slowly build up with increasing missing momentum p_m. We found a large contribution to the p_m distribution in transverse kinematics from the novel effect of the quantum mechanical interference of FSI and ISC effects. The considered aspects of ISC and FSI were not discussed in previous work on FSI and ISC effects in $A(e, e'p)$ scattering [16,17,18]. Our results suggest that the experimental separation of the FSI and ISC effects is more difficult than thought before. The expansion parameter of the problem $\sim r_c/R_o$ is not very small, and more detailed numerical analysis with allowance for the tensor correlation function and the D-wave in ^4He are called upon to establish the sensitivity to models for the correlation function. The implications of the attenuation, distortion and forward-backward asymmetry effects for the y-scaling analysis in terms of the undistorted ISC effect will be presented elsewhere.

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Fig. 1 The angular dependence of the three most important components of $w(\vec{p}_m)$ at $p_m = 2fm^{-1}$ (lower panel) and at $p_m = 3fm^{-1}$ (upper panel). The dotted line is the undistorted distribution $n_F(p_m)$ taken from [7], the dash-dotted line represents the ISC-FSI interference component $w(C\Gamma' + C'\Gamma; \vec{p}_m)$, the dashed line shows the elastic rescattering component $w(\Gamma'\Gamma; \vec{p}_m)$, and the solid line is the sum of the three contributions.

Fig. 2 The angular dependence of the elastic rescattering term $w(\Gamma'\Gamma; \vec{p}_m)$ including the product $\theta(z_i - z_4)$ and $\theta(z_i' - z_4)$ (solid line) and replacing the product of the θ -functions by $\frac{1}{4}$ (dotted line) for $p_m = 2fm^{-1}$ (lower panel) and $p_m = 3fm^{-1}$ (upper panel).

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